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SUSY searches : the LEP legacy

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Abstract

A wide range of supersymmetric searches has been performed at LEP. The negative outcome of those searches has been translated into indirect constraints on the lightest neutralino, $\tilde{\chi}_1^0$, a good supersymmetric candidate for the cold dark matter. After presenting the LEP experimental environment, the $\tilde{\chi}_1^0$ lower mass limit within different theoretical assumptions will be reviewed.

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SUSY SEARCHES: THE LEP LEGACY

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A wide range of supersymmetric searches has been performed at LEP. The negative outcome of those searches has been translated into indirect constraints on the lightest neutralino, $\tilde{\chi}_1^0$, a good supersymmetric candidate for the cold dark matter. After presenting the LEP experimental environment, the $\tilde{\chi}_1^0$ lower mass limit within different theoretical assumptions will be reviewed

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Key words: SUSY, LEP, DARK MATTER

1 Introduction

Charginos, neutralinos, scalar leptons and scalar top and bottom quarks have been searched at LEP, within different SUSY breaking scenarios (SUGRA or GMSB), assuming either R-parity conservation or R-parity violation in the framework of SUGRA models. In this present report, I will concentrate on searches assuming R-parity conservation within the mSUGRA framework. Supersymmetry theory provides a good candidate to the cold dark matter: the Lightest Supersymmetric Particle (LSP). Under the R-parity conservation assumption the LSP is stable. Due to the strong experimental constraints on stable charged particles, the LSP is most probably neutral. The lightest neutralino $\tilde{\chi}_1^0$ is a good LSP candidate and gives relic density Ωh^2 compatible with measurements for a wide range of the parameter space. Since the $Z\tilde{\chi}_1^0\tilde{\chi}_1^0$ coupling is suppressed and the $\tilde{\chi}_1^0$ escapes detection (neutral and weakly interacting), the $\tilde{\chi}_1^0\tilde{\chi}_1^0$ direct search at LEP was disfavoured. Nevertheless, the LEP sensitivity for chargino, slepton or stop and sbottom quark searches was optimal. By exploiting the mass and coupling of each SUSY particle dependence with the SUSY parameters, indirect constraints on the $\tilde{\chi}_1^0$ mass have been derived. The robustness of those constraints is discussed for the different theoretical model assumptions.

2 Searches at LEP

2.1 The Large Electron Positron collider: LEP

The LEP accelerator the CERN synchrotron electron-positron collider, has started operation in 1989. The data taking has ended on November 2000. The two phases of LEP operation were:

- LEP1 (1989-1995) where millions of Z events have been accumulated for high precision measurements with an integrated luminosity of roughly 175 inverse picobarn (pb^{-1}) collected per experiment.
- LEP2 (1996-2000) where the centre-of-mass energy (\sqrt{s}) has been increased from 130 GeV to 208 GeV extending the new particle search area. In the meantime the integrated luminosity collected per year and per experiment increased from 5 pb^{-1} to 250 pb^{-1} . LEP2 was a real success and went far beyond the nominal goals.

2.2 The Four LEP experiments: ADLO

Four experiments have been installed on the LEP: ALEPH, DELPHI, L3 and OPAL. Each detector was designed to cover a large solid angle, to identify and reconstruct electrons, photons, muons, to tag heavy flavor (τ and b-quark) and to reconstruct hadron jet. In contrast with the hadron colliders, the trigger criteria were simple and all the physics was recorded leading to a trigger efficiency of 100 % (for events with a deposited energy greater than 3 GeV).

3 Sensitivities

The sensitivity is a function of the signal cross section production, the signal efficiency and the background. The visible energy and the particle multiplicity will be almost proportional to the mass difference between the SUSY particle and the $\tilde{\chi}_1^0$:

$$\Delta M = M_{\tilde{P}} - M_{\tilde{\chi}_1^0}$$

Thus the search strategy and the sensitivity will depend on this ΔM parameter.

3.1 Cross section production and decay modes

- Chargino and Neutralino: Charginos ($\tilde{\chi}_{1,2}^\pm$), the supersymmetric partners of W^\pm and H^\pm , are pair produced via s -channel γ/Z exchange. The production cross section can be reduced by an order of magnitude when the t -channel scalar neutrino ($\tilde{\nu}$) exchange is important. Neutralinos, the supersymmetric partners of Z, γ , and neutral Higgs bosons, are pair produced $e^+e^- \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^0$ ($i, j = 1, \dots, 4$; ordered by their masses) via s -channel Z exchange and their production cross section can be enhanced by t -channel exchange of a scalar electron (\tilde{e}^\pm).
- Sfermion pairs: The pair production of scalar fermion proceeds through the s -channel γ or Z exchange. For scalar electrons, the production cross section is enhanced by the t -channel exchange of a neutralino. At LEP energies, all scalar fermions, but the scalar top, decay into their SM partners mainly via $\tilde{f} \rightarrow \tilde{\chi}_1^0 f$, but also via cascade decays, such as $\tilde{f} \rightarrow \tilde{\chi}_2^0 f \rightarrow \tilde{\chi}_1^0 Z^* f$, which

may dominate in some regions of the parameter space of the MSSM. Four channels dominate among the possible scalar top decays: $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$, $b\nu_{\ell}\tilde{\ell}$, $b\ell\tilde{\nu}_{\ell}$, and $b\tilde{\chi}_1^+$.

3.2 SUSY event topologies

The list of the processes accessible at LEP II is given in Table 1 as well as the decay channels. The main features of the SUSY searches performed at LEP can be summarized as follows:

- Under R-parity conservation each particle are pair produced and decays into the $\tilde{\chi}_1^0$ and their associated partner of the Standard Model. Since the $\tilde{\chi}_1^0$ escapes detection, the SUSY final state topologies are characterized by missing energy and acoplanar objects (hadronic jets or leptons). The key point for each LEP detector was the hermiticity.
- The number of final states is large: ranging from the simple acoplanar lepton pair to the multijets plus missing energy final state or photon plus missing energy events. This large variety of explored signatures was the strength of the SUSY searches performed at LEP. Thus the complementarity of the SUSY processes was exploited in an optimal way.

Processus	Decay channel	Final State-Topology
$e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$	$\tilde{\chi}_1^+ \rightarrow W^{*+} \tilde{\chi}_1^0$ $W^{*+} \rightarrow l^+ \nu$ $W^{*+} \rightarrow q^1 \bar{q}^2$ $W^{*+} \rightarrow q^1 \bar{q}^2$	Acoplanar lepton pairs plus \cancel{E} Four hadronic jets plus \cancel{E} Two jets plus one lepton plus \cancel{E}
$e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- (\gamma_{\text{isr}})$	$\tilde{\chi}_1^+ \rightarrow W^{*+} \tilde{\chi}_1^0$ $M_{\tilde{\chi}_1^+} \sim M_{\tilde{\chi}_1^0}$	γ plus soft particle + \cancel{E}
$e^+e^- \rightarrow \tilde{\chi}_{j \geq 2}^0 \tilde{\chi}_{i \geq 1}^0$	$\tilde{\chi}_{j \geq 2}^0 \rightarrow Z^{*+} \tilde{\chi}_1^0$ $Z^* \rightarrow l^+ l^-$ $Z^* \rightarrow q \bar{q}$	Acoplanar lepton pairs plus \cancel{E} Acoplanar jet pairs plus \cancel{E}
$e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^0$	$\tilde{\chi}_2^0 \rightarrow \gamma + \tilde{\chi}_1^0$	Photon plus \cancel{E}
$e^+e^- \rightarrow \tilde{\ell}^+ \tilde{\ell}^-$	$\tilde{\ell}^+ \rightarrow l^+ \tilde{\chi}_1^0$ $l = \mu, e, \tau$	Acoplanar lepton pairs plus \cancel{E}
$e^+e^- \rightarrow \tilde{q} \tilde{q}$	$\tilde{q} \rightarrow q + \tilde{\chi}_1^0$ $\tilde{q} = \tilde{t}_1, \tilde{b}$	Acoplanar hadronic pairs plus \cancel{E}

3.3 Background

The signal topologies and the associated background sources change for different ΔM ranges. In the low and very low ΔM ranges, the expected topologies for the signal are characterized by a low multiplicity and a low visible energy, and the

background is dominated by the two-photon interactions. For high ΔM ranges, the signal signatures are very similar to those of W-pair production; in particular for $\Delta M > 80$ GeV on-shell Ws are produced. For intermediate ΔM the best sensitivity is achieved since the background is minimal. The cross section production measurements at different centre-of-mass energies for each process are in a very good agreement with theoretical predictions as depicted on Fig. 1 (left side).

3.4 Results

No excess of events has been observed in any channel and any experiment thus upper limits on the chargino, neutralino and slepton production cross sections have been set. Exclusion limits at 95% C.L. are derived taking into account background contributions and derived in the $(M_{\tilde{\chi}_1^0}, M_{\tilde{e}})$ plane since the detection sensitivity depends on both parameters. The “standard” chargino search sensitivity is illustrated on Fig. 1: the best sensitivity is achieved for the intermediate ΔM regions, where the background is low and the efficiency greater than 40% leading to cross section upper limits as low as 0.15 pb^{-1} . For large ΔM values, the signal efficiency is still high ($\sim 40\%$) but the WW background remains irreducible leading to cross section upper limits ranging from 0.5 to 0.7 pb^{-1} . For the low ΔM values, it becomes even worst dealing with a huge background and a poor trigger efficiency: low particle multiplicity and low deposited energy make the trigger inefficient. The sensitivity becomes very low yielding cross section upper limits of the order of 2 pb^{-1} for $\Delta M \sim 5$ GeV.

In the ΔM regions below 3 GeV, classical SUSY searches, so called standard, were blind. Introducing the Initial State Radiation (ISR)- γ analysis, some sensitivity has been recovered by increasing the trigger efficiency and reducing the two-photon interaction background (despite a 90% reduction of the signal cross section production). Upper limits on sfermion cross section productions have been also derived and combined early by the four LEP experiments [7] since for scalar particles the integrated luminosity matters above all.

4 SUSY particle mass limits

In the MSSM, with Grand Unification assumption, the masses and couplings of the SUSY particles as well as their production cross sections, are entirely described once five parameters are fixed: $\tan \beta$ (the ratio of the vacuum expectation values of the two Higgs doublets), $M \equiv M_2$ (the gaugino mass parameter), μ (the higgsino mixing parameter), m_0 (the common mass for scalar fermions at the GUT scale) and A (the trilinear coupling in the Higgs sector). We investigate the following MSSM parameter space:

$$\begin{array}{lll} 0.7 \leq \tan \beta \leq 60, & 0 \leq M_2 \leq 2000 \text{ GeV}, \\ -2000 \text{ GeV} \leq \mu \leq 2000 \text{ GeV}, & 0 \text{ GeV} \leq m_0 \leq 500 \text{ GeV}. \end{array}$$

The impact of the maximal mixing in the stau sector has not been included in what follows but has been studied in [1], [3] and [4] experiments where it was

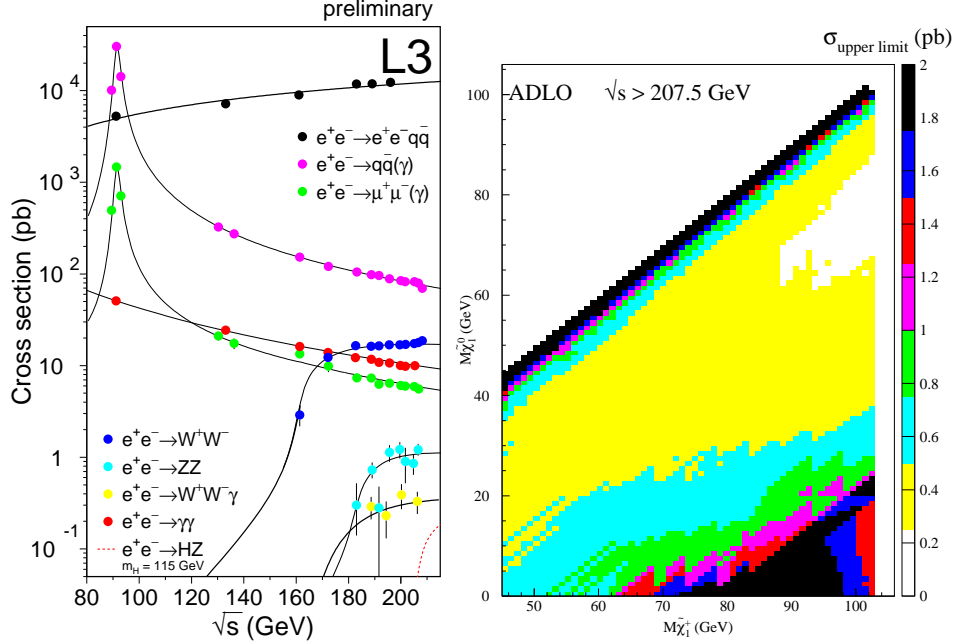


Figure 1. Left: Cross section production measurements at different centre-of-mass energies for each process of the Standard Model [4] Right: The Observed Upper limit on the $e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$ cross section production assuming a $\text{br}(\tilde{\chi}_1^+ \rightarrow W^+ \tilde{\chi}_1^0) = 100\%$ with ADLO at the highest centre-of-mass energy [7]

shown that the limits remain robust.

To derive the absolute mass limits of the lightest neutralino, a scan in the MSSM parameter space is performed in steps of 0.2 GeV for M_2 , 1.0 GeV for μ and 0.5 GeV for m_0 .

All the limits on the cross sections have been translated into exclusion regions in the MSSM parameter space. To derive such limits, the cross sections and branching fractions have been calculated in the MSSM framework.

In what follows the μ parameter is free (No dynamic EWSB) which is equivalent to vary A_0 in fact. When imposing the dynamic EWSB, μ but the sign is no more a free parameter and we are in the more constrained mSUGRA framework. Exhaustive interpretations of the LEP results has been performed in this framework and are reviewed in [8] but will not be described in what follows.

4.1 Scalar Leptons (\tilde{e} , $\tilde{\tau}$, $\tilde{\mu}$) mass limits

Due to the β^3 dependence of the cross section production, the collected luminosity matters mainly. For this reason, LEP analyses were combined at the very begin-

ning of the LEP working group activity. In the hypothesis $\tan \beta > 1$ SUSY partners of the right-handed leptons, $\tilde{\ell}_R^\pm$, are expected to be lighter than their left-handed counterparts. Figure 2 shows the exclusion contours in the $M_{\tilde{\chi}_1^0} - M_{\tilde{\ell}_R^\pm}$ plane considering only the reaction $e^+e^- \rightarrow \tilde{\ell}_R^\pm \tilde{\ell}_R^\mp$ for $\mu = -200$ GeV and $\tan \beta = 1.5$. These exclusions also hold for higher $\tan \beta$ and $|\mu|$ values.

Under these assumptions, lower limits on scalar lepton masses are derived. Scalar electrons lighter than 99.4 GeV, for $\Delta M > 10$ GeV, scalar muons lighter than 96.5 GeV, for $\Delta M > 10$ GeV, and scalar taus lighter than 91.7 GeV for $\Delta M > 15$ GeV are excluded at 95 % C.L.

The limiting factor towards an absolute limit on the scalar electron mass is the lack of detection efficiency for very small ΔM values. This can be overcome in the constrained MSSM by taking profit of the $e^+e^- \rightarrow \tilde{e}_R \tilde{e}_L$ process whose selection is discussed above. The searches for acoplanar electrons and single electrons are combined to derive a lower limit on $M_{\tilde{e}_R}$ as a function of $\tan \beta$ and for any value of m_0 , M_2 and μ [2] and [5]. For $\tan \beta \geq 1$, the lower limit for the lightest scalar electron independent of the MSSM parameters is: $M_{\tilde{e}_R} \geq 73$ GeV.. Assuming a common mass for the scalar leptons at the GUT scale, this limit holds also for the lightest scalar muon, $\tilde{\mu}_R$.

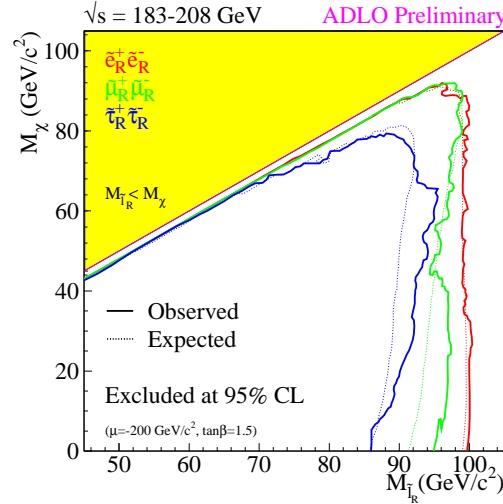


Figure 2. ADLO combined excluded region at 95% C.L. in the $M_{\tilde{\chi}_1^0} - M_{\tilde{l}}$ plane, for the three scalar lepton flavors

4.2 \tilde{t}_1 and \tilde{b}_1 mass limits

In the MSSM scalar quark top and sbottom production cross sections depend on their masses and the mixing angle $\cos \theta_{LR}$. Comparing these predictions with lim-

its on the production cross section, the excluded mass regions for \tilde{t}_1 and \tilde{b}_1 are determined.

Figure 3(left side) shows the excluded \tilde{t}_1 mass region in the $M_{\tilde{t}_1}$ - $M_{\tilde{\chi}_1^0}$ plane at $\cos\theta_{LR}=1$ and 0.57 for the $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$ decay. The second value of the mixing angle corresponds to a vanishing contribution of the Z exchange in the s-channel. For this decay mode, scalar top masses below 98 GeV are excluded under the assumptions $\cos\theta_{LR}=1$ and $\Delta M = 40$ GeV. For the same values of ΔM and in the most pessimistic scenario of $\cos\theta_{LR}=0.57$, the mass limit is 95 GeV. The region where $\tilde{t}_1 \rightarrow bW\tilde{\chi}_1^0$ decay is kinematically accessible and becomes the dominant decay mode, is indicated. This decay is not considered in the analysis.

Figure 3 (right side) shows the excluded region considering scalar bottom decays into bottom quark and the lightest neutralino for $\cos\theta_{LR}=1$ and $\cos\theta_{LR}=0.39$, which also corresponds to a pure γ exchange. Sbottom masses below 99 GeV are excluded assuming $\cos\theta_{LR}=1$ and $\Delta M = 15 - 25$ GeV. In the most pessimistic scenario of $\cos\theta_{LR}=0.39$, the mass limit obtained is 95 GeV.

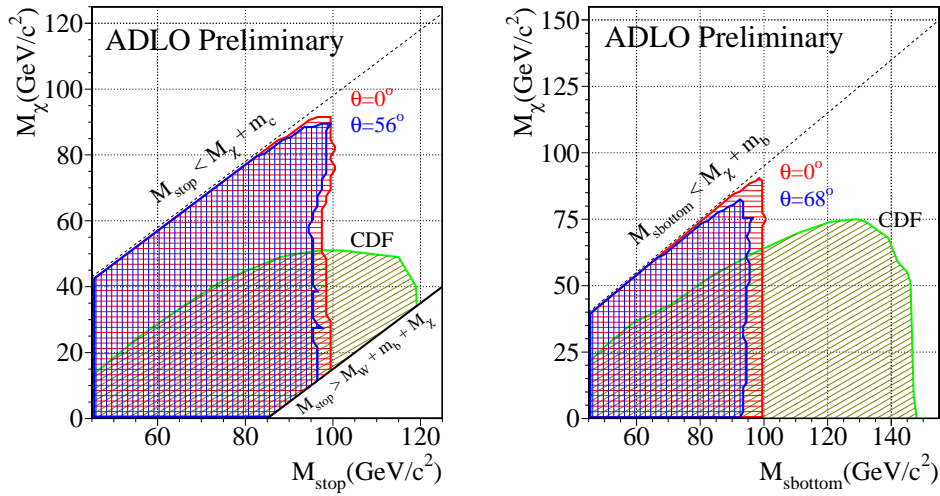


Figure 3. ADLO Combined excluded regions in the $M_{\tilde{t}_1}$ - $M_{\tilde{\chi}_1^0}$ plane(left side) $M_{\tilde{b}_1}$ - $M_{\tilde{\chi}_1^0}$ plane (right side) for different values of the mixing angle.

The excluded stop mass regions, if the dominant three-body decays are kinematically open, have been determined assuming $\tilde{t}_1 \rightarrow b\ell\tilde{\nu}$ equal branching fractions for the decays into e, μ or τ . Here the lower \tilde{t}_1 mass limits are 99 GeV and 97 GeV for $\cos\theta_{LR}=1$ and 0.57, respectively.

Assuming gaugino unification at the GUT scale, the results on the four degenerate squarks are reinterpreted on the $M_{\tilde{g}}$, $M_{\tilde{q}}$ plane. Moreover, the gaugino

unification allows a transformation of the absolute limit on M_2 , obtained from the chargino, neutralino and scalar lepton searches, into a limit on the gluino mass. For $\tan\beta = 4$, gluino masses up to about 270–310 GeV are excluded at 95% C.L. [5].

4.3 $\tilde{\chi}_1^1$ and $\tilde{\chi}_1^0$ mass limits

4.4 Large scalar mass or Large m_0

The slepton within this assumption are out of the kinematic reach, the mean sensitivity is given by the chargino searches. Since the cross section production depends on the chargino field contents, different $\tilde{\chi}_1^0$ mass limits are set.

- Deep Gaugino Chargino ($\mu \gg M_2$): This is the optimal scenario, the cross section production is the highest, the ΔM intermediate leading to the best sensitivity: the chargino is at the kinematic reach thus it is important to reach the highest center of mass energy. Combining the four LEP experiments at $\sqrt{s} > 207.5$ GeV with an overall luminosity of 32 pb^{-1} chargino lighter than 103.5 GeV is excluded leading to $\tilde{\chi}_1^0$ mass limit of 52 GeV [7] as depicted on Fig 4.
- Deep Higgsino Chargino ($\mu \gg M_2$): Within the scenario, the limit on chargino mass is obtained when the chargino and the $\tilde{\chi}_1^0$ are mass degenerate. A limit independent on ΔM on the chargino mass has been set by each experiment: $M_{\tilde{\chi}_1^\pm} > 85$ GeV, thanks to the ISR γ analysis. The LEP combined limit is equal to 92.4 GeV as shown on Fig 4. Thus the limit on the $\tilde{\chi}_1^0$ mass should be greater than 90 GeV in this scheme.
- Mixed Higgsino-Gaugino Chargino ($\mu \sim M_2$): For a given chargino mass, the mass of the $\tilde{\chi}_1^0$ is minimal for $\mu \sim -M_2$ and $\tan\beta=1$. For those parameter ranges, the chargino and neutralino searches are complementary as depicted in Fig 5, left side, where the neutralino process allow to go beyond the chargino kinematic limit. $\tilde{\chi}_1^0$ mass limits ranging from 37 to 39.6 GeV are obtained by the four experiments. The $\tan\beta$ dependence is illustrated on Fig. 5 on the right side.

4.4.1 Low scalar mass or Low m_0

For low m_0 values, sleptons are light and within reach of LEP energies. When combining slepton, chargino and neutralino searches, the weakest sensitivity is found to be when the $\tilde{\chi}_1^\pm$, the $\tilde{\nu}$ and the $\tilde{\chi}_1^0$ are mass degenerate: $\tilde{\chi}_1^+$ becomes invisible and is produced with a low rate, $\tilde{\chi}_2^0$ decaying into $\tilde{\nu}, \nu$ is also invisible, the sensitivity is then recovered with the sleptons. The indirect limit on the $\tilde{\chi}_1^0$ mass is then given through the M_2 dependence on the selectron mass. On Fig 5 left side, one can see how the $\tilde{\chi}_1^0$ mass limit is affected at high $\tan\beta$ values when scanning over all the m_0 values.

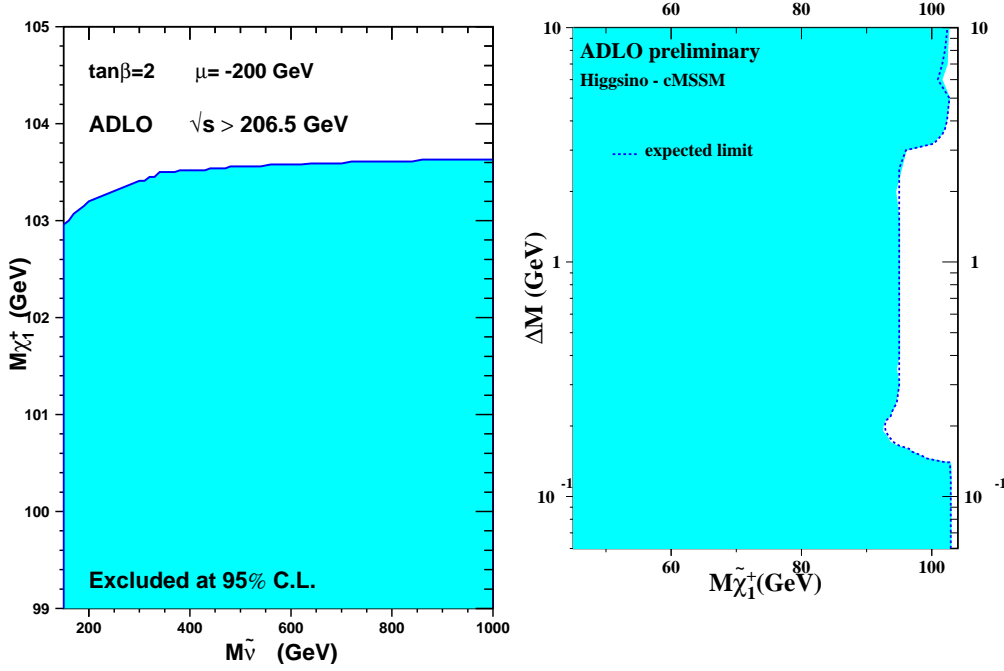


Figure 4. Chargino mass limit as a function of $M_{\tilde{\nu}}$ (left side) and as a function of ΔM including the ISR analysis and the Long lived particle analysis (left side)

4.4.2 The impact of Higgs boson search

At the tree level, the lighter CP-even Higgs boson mass depends only on the mass m_A of the CP-odd Higgs boson and on $\tan\beta$. The value of m_h ranges from zero for $m_A=0$, to a maximum value of $m_Z|\cos 2\beta|$ for very large values of m_A . Thus, a lower limit on m_h can be translated into a lower limit on $\tan\beta$. When including the radiative corrections due to the large top quark mass, m_h^2 receives an additional contribution proportional to $m_t^4 \log(m_{\tilde{t}}^2)$, assuming the two stops are mass-degenerate. It appears that for stop not much heavier than top quark, this correction remains small to still allow a lower limit on $\tan\beta$ to be derived [1]. Alternatively, for low $\tan\beta$ value, a minimum value for $m_{\tilde{t}}$ can be inferred from the lower limit on m_h . This $m_{\tilde{t}}$ lower limit through its dependence with M_2 can be translated into a lower limit on the $\tilde{\chi}_1^0$ mass for a given range of m_0 .

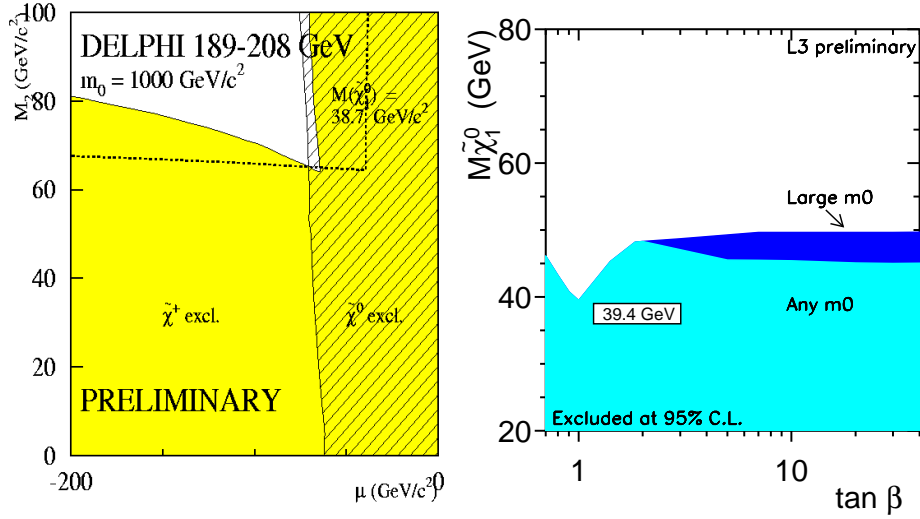


Figure 5. $\tilde{\chi}_1^0$ mass limit in the (μ, M_2) plane for $\tan\beta=1$ [3] (left side) and as a function of $\tan\beta$ [4] (right side)

As can be seen in Fig 6, the $\tilde{\chi}_1^0$ mass limit is improved in the low $\tan\beta$ region with the Higgs boson searches leading to a mass limit of 50 GeV for $\tan\beta$ values less than 3. Finally the absolute lower mass limit on the $\tilde{\chi}_1^0$ is found to be equal to 47 GeV resulting from the combination of the Slepton, Higgs boson and Chargino searches performed by the ADLO experiments [1] and [7]. This limit holds for any $m_0 \leq 1$ TeV and $m_t=175$ GeV. For m_0 values larger than 2 TeV, the Higgs boson searches no longer improve on the $\tilde{\chi}_1^0$ mass limit at low $\tan\beta$ deduced from with chargino and neutralino searches.

5 Conclusion

A wide variety of searches has been carried out at LEP2 and despite all the efforts, no indication for new physics has been observed up to 208 GeV. LEP2 was an unique place for SUSY searches: Due to the good detector performances and the relatively good knowledge of the background reactions, a large domain has been covered and all channels have been exploited. With the absence of any signal, LEP2 excluded chargino masses up to the kinematic limit (103.5 GeV) for most of the SUSY parameter space, even better an absolute limit has been obtained ~ 90 GeV irrespective of ΔM value. In addition, an indirect and absolute lower limit, equal to 39.6 GeV on the Lightest Susy Particle has been derived in the framework of the CMSSM. By including the Higgs searches, this limit becomes 47 GeV and is

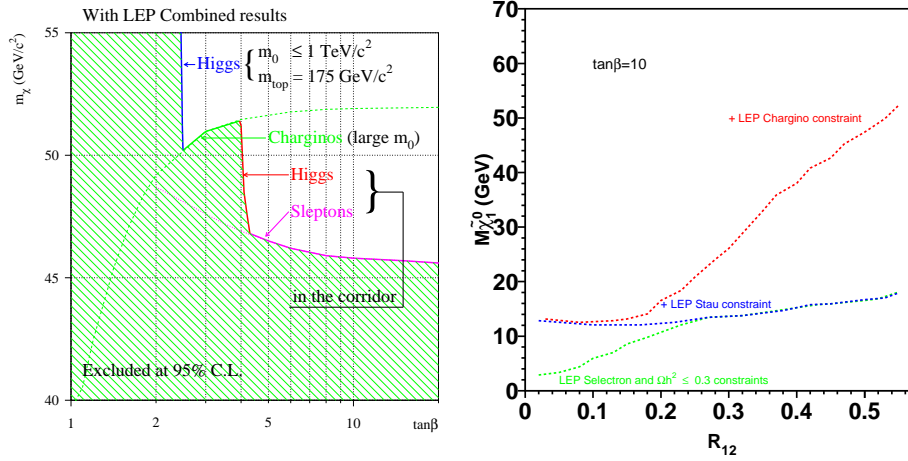


Figure 6. Mass limit on the $\tilde{\chi}_1^0$ including Chargino, Higgs and sleptons searches at LEP [7] (left side) and when relaxing the gaugino mass unification at the GUT scale [9] (right side)

obtained at large $\tan\beta$ values but holds for any $m_0 \leq 1$ TeV and $m_t=175$ GeV. In order to test the robustness of this limit, a first attempt has been made to relax the gaugino mass unification assumption by decreasing the parameter $R_{12}=M_1/M_2$ from 0.55 (value at the EW scale within the GUT unification assumption) to 0.1 values. By combining the constraint on the relic density $\Omega h^2 < 0.3$ [9] with the LEP constraints the $\tilde{\chi}_1^0$ mass limit becomes 12 GeV irrespective of R_{12} as depicted on Fig 6.

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